The inertial navigation can also be done as the logging sonde is withdrawn from the borehole. When the borehole's starting surveyed point is reached, the location information and a gyrocompass done at that point can be used to adjust the navigation solution back down the borehole, which is known as Kalman smoothing.

It should be apparent to those skilled in the art that the navigation systems described herein may not only be used within a borehole environment, but can be used in any environment, such as, for example, an environment that requires a navigation system having a small size and long term performance requirements with only short term requirements on the inertial sensors. One such environment may be robotics or personal navigation.

Although specific features of the invention are shown in some drawings and not in others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention. The words "including", "comprising", "having", and "with" as used herein are to be interpreted broadly and comprehensively and are not limited to any physical interconnection. Moreover, any embodiments disclosed in the subject application are not to be taken as the only possible embodiments.

Other embodiments will occur to those skilled in the art and are within the following claims.

What is claimed is:

1. An omnidirectional borehole navigation system comprising:

a housing for traversing a borehole;

a gimbal system including at least one outer gimbal connected to said housing and at least one inner gimbal nested in and connected to said outer gimbal;

a solid state three-axis gyro assembly mounted on said at least one inner gimbal;

a solid state three-axis accelerometer assembly mounted on said inner gimbal;

gyro logic circuits on said at least one inner gimbal responsive to said three-axis gyro assembly to produce the inertial angular rate about each gyro input axis;

accelerometer logic circuits on said at least one inner gimbal to produce the non-gravitational acceleration along each accelerometer input axis; and

a microprocessor responsive to said gyro logic circuits and said accelerometer logic circuits for determining the attitude and the position of said housing in its borehole.

2. The omnidirectional borehole navigation system of claim 1 in which said housing includes a pressure vessel.

3. The omnidirectional borehole navigation system of claim 1 in which said

housing includes a Dewar vacuum jacket.

4. The omnidirectional borehole navigation system of claim 1 in which said housing includes a standoff structure for spaceably interconnecting said housing with a borehole drill pipe.

5. The omnidirectional borehole navigation system of claim 4 in which the space between said housing and said drill pipe forms a drilling mud flow channel.

6. The omnidirectional borehole navigation system of claim 1 in which said outer gimbal axis extends longitudinally along said housing.

7. The omnidirectional borehole navigation system of claim 1 in which said inner gimbal axis extends laterally to said housing.

8. The omnidirectional borehole navigation system of claim 1 in which said outer gimbal includes a drive motor for rotating said outer gimbal with complete rotary freedom.

9. The omnidirectional borehole navigation system of claim 1 in which said at least one inner gimbal includes a drive motor for rotating said inner gimbal.

10. The omnidirectional borehole navigation system of claim 1 in which said

at least one inner gimbal is rotatable 180° in each direction.

11. The omnidirectional borehole navigation system of claim 1 in which said at least one inner gimbal includes a twist capsule device and said outer gimbal includes a slip ring device for electrically interconnecting said gyro and accelerometer logic circuits with said microprocessor.

12. The omnidirectional borehole navigation system of claim 1 in which at least one of the gimbals is equipped with gimbal angle readouts.

13. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis gyro system includes three, one-axis gyros.

14. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis gyro system includes a MEMS gyro system.

15. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis gyro system includes a laser gyro system.

16. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis gyro system includes a quartz gyro system.

17. The omnidirectional borehole navigation system of claim 1 in which said

solid state three-axis accelerometer system includes three, one-axis accelerometers.

18. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis accelerometer system includes a MEMS accelerometer system.

19. The omnidirectional borehole navigation system of claim 1 in which said solid state three-axis accelerometer system includes a quartz accelerometer system.

20. The omnidirectional borehole navigation system of claim 1 in which said gyro logic circuits include a field programmable gate array.

21. The omnidirectional borehole navigation system of claim 1 in which said gyro logic circuits include an application-specific integrated circuit.

22. The omnidirectional borehole navigation system of claim 1 in which said accelerometer logic circuits include a field programmable gate array.

23. The omnidirectional borehole navigation system of claim 1 in which said accelerometer logic circuits include an application-specific integrated circuit.

24. The omnidirectional borehole navigation system of claim 1 in which said at least one inner gimbal includes a plurality of stacked gimbal elements, one corresponding to each gyro axis and accelerometer axis.

25. The omnidirectional borehole navigation system of claim 1 in which said microprocessor commands carouseling and indexing of said gimbals to average out the effect of gyro and accelerometer system bias errors.

26. The omnidirectional borehole navigation system of claim 1 in which said microprocessor commands rotation of said gimbals to determine north and vertical directions and to calibrate the gyro and accelerometer biases, to effect gyrocompassing, and to calibrate gyro scale factors.

27. The omnidirectional borehole navigation system of claim 1 in which said microprocessor also determines the velocity of said housing in its borehole.

28. An omnidirectional borehole navigation system comprising:

a housing for traversing a borehole;

a dual gimbal system including an outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal;

a MEMS three-axis gyro assembly mounted on said inner gimbal;

a MEMS three-axis accelerometer assembly mounted on said inner gimbal;

gyro logic circuits on said inner gimbal responsive to said three-axis gyro assembly to produce the inertial angular rate about each gyro input axis;

accelerometer logic circuits on said inner gimbal to produce the non-gravitational acceleration along each accelerometer input axis; and

a microprocessor responsive to said gyro logic circuits and said accelerometer logic circuits for determining the attitude, the position, and the velocity of said housing in its borehole.

29. The omnidirectional borehole navigation system of claim 28 in which said outer gimbal axis extends longitudinally along said housing.

30. The omnidirectional borehole navigation system of claim 28 in which said inner gimbal axis extends laterally to said housing.

31. The omnidirectional borehole navigation system of claim 28 in which said gyro logic circuits include a field programmable gate array.

32. The omnidirectional borehole navigation system of claim 28 in which said gyro logic circuits include an application-specific integrated circuit.

33. The omnidirectional borehole navigation system of claim 28 in which said accelerometer logic circuits include an application-specific integrated circuit.

34. The omnidirectional borehole navigation system of claim 28 in which said accelerometer logic circuits include a field programmable gate array.

35. An omnidirectional borehole navigation system comprising:

a housing for traversing a borehole;

a gimbal system including an outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal, said inner gimbal including a plurality of stacked inner gimbal elements;

a MEMS three-axis gyro assembly, each axis of said gyro assembly mounted on one of said stacked inner gimbal elements;

a MEMS three-axis accelerometer assembly mounted on said inner gimbal, each axis of said accelerometer assembly mounted on one of said stacked inner gimbal elements;

gyro logic circuits on said inner gimbal responsive to said three-axis gyro assembly to produce the inertial angular rate about each gyro input axis;

accelerometer logic circuits on said inner gimbal to produce the non-gravitational acceleration along each accelerometer input axis; and

a microprocessor responsive to said gyro logic circuits and said accelerometer logic circuits for determining the attitude, the position, and the velocity of said housing in its borehole.

36. The omnidirectional borehole navigation system of claim 35 in which each of said stacked inner gimbals includes a drive motor for rotating the corresponding inner gimbal element.

37. The omnidirectional borehole navigation system of claim 35 in which said stacked inner gimbals include a drive motor for rotating each of said stacked inner gimbal elements.

38. An omnidirectional borehole navigation system comprising:

a housing for traversing a borehole;

a gimbal system including at least one outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal;

a solid state three-axis gyro assembly mounted within said housing;

a solid state three-axis accelerometer assembly mounted within said housing;

gyro logic circuits mounted within said housing and responsive to said three-axis gyro assembly to produce the inertial angular rate about each gyro input axis;

accelerometer logic circuits mounted within said housing and responsive to said three-axis accelerometer assembly to produce the non-gravitational acceleration along each accelerometer input axis; and

a microprocessor responsive to said gyro logic circuits and said accelerometer logic circuits for determining the attitude, the position, and the velocity of said housing in its borehole.

39. The omnidirectional borehole navigation system of claim 38 in which said three-axis gyro assembly and said three-axis accelerometer assembly are mounted on said inner gimbal.

40. A method for borehole navigation, comprising the steps of:

providing a housing for traversing a borehole, the housing including a gimbal system having at least one outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal, said gimbal system including a solid state three-axis gyro assembly and a solid state three-axis accelerometer assembly mounted within said gimbal system;

obtaining information about a position of a first point in the borehole;

determining the attitude of the first point in the borehole using said three-axis gyro assembly and said three-axis accelerometer assembly by rotating said gimbal system through four or more gyrocompass positions to determine gyro and accelerometer biases, and the Earth's rotation and gravity vectors;

traversing through the borehole to a second point in the borehole;

determining the attitude at the second point in the borehole using said three-axis gyro assembly and said three-axis accelerometer assembly; and

determining the position of the second point in the borehole based upon information about the attitude at the first and second points in the borehole and the distance traversed from the first position to the second position in the borehole.

41. The method for borehole navigation of claim 40, further including the step of calibrating the gyro scale factors from the slews between gyrocompass positions.

42. A method for borehole navigation, comprising the steps of:

providing a housing for traversing a borehole, the housing including a gimbal system having at least one outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal, said gimbal system including a solid state three-axis gyro assembly and a solid state three-axis accelerometer assembly mounted within said gimbal system;

obtaining information about a position of a first point in the borehole;

determining the attitude of the first point in the borehole using said three-axis gyro assembly and said three-axis accelerometer assembly by rotating said gimbal system through four or more gyrocompass positions to determine gyro and accelerometer biases, and the Earth's rotation and gravity vectors;

while traversing through the borehole and carouseling and/or indexing the gimbals, determining the attitude using outputs of said three-axis gyro assembly and propagating the position using the increment of drill pipe advance times the attitude; and

Kalman filter updating the position of a second point in the borehole based upon the propagated position from the first point, information about the attitude from a gyrocompass at the second point, and the distance traversed from the first point to the second point in the borehole.

43. The method for borehole navigation of claim 42, further including the step of calibrating the gyro-scale factors from the slews between gyrocompass positions.

44. A method for borehole navigation comprising the steps of:

providing a housing for traversing a borehole, the housing including a gimbal system having at least one outer gimbal connected to said housing and an inner gimbal nested in and connected to said outer gimbal, said gimbal system including a solid state three-axis gyro assembly and a solid state three-axis accelerometer assembly mounted within said gimbal system;

determining the attitude at the first point in the borehole using said three-axis gyro assembly and three-axis accelerometer assembly by rotating said gimbal system through four or more gyrocompass positions to determine gyro and accelerometer biases, and the Earth's rotation and gravity vectors;

while traversing through the borehole and carouseling and/or indexing the gimbals, determining the attitude, position, and velocity by inertial navigation algorithms using the outputs of said three-axis gyro assembly and said three-axis accelerometer assembly to obtain an inertial navigation solution, and Kalman filter updating the inertial navigation solution using the increment of a drill pipe advance external aid; and

Kalman filter updating the position of a second point in the borehole based upon the inertial navigation result for the second point, information about attitude from a gyrocompass at the second point, and the distance traveled from the first point to the second point in the borehole.

45. The method for borehole navigation of claim 44, further including the step of calibrating the gyro scale factors from the slews between gyrocompass positions.